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(54) **Backing layer for acoustic transducer array.**

(57) The invention provides an acoustic transducer for transmitting acoustic wave energy in response to an electrical signal and for converting the received acoustic wave energy into an electric signal. The transducer includes an array of piezoelectric elements (52), a backing layer (30) attached at a rearward face of the piezoelectric elements, a circuit element (54) spaced apart from the piezoelectric elements (52) by the backing layer (30), and at least one electrical conductor (24) for each of the piezoelectric elements (52) to connect the elements to the circuit element (54). The backing layer (30) comprises a plurality of layers (10) of acoustic attenuating material integrally formed into a laminate structure. The electrical conductors (24) extend along a surface of each of the layers (10) and have a predetermined pitch. Each of the layers (10) has a thickness substantially equivalent to the pitch of the electrical conductors (24). Individual piezoelectric elements (52) are formed on the upper surface (32) of the laminate structure (30), and conductive pads (46) are formed on the lower surface (34) of the laminate structure. The electrical conductors (24) provide electrical connection through the backing layer (30) between the piezoelectric elements (52) and the associated conductive pads (46).

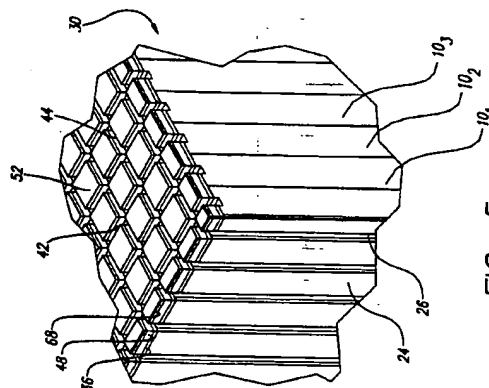


FIG. 5

This invention relates to acoustic transducer arrays, and more Particularly, to a laminated backing layer for use with such arrays to electrically connect the array to a circuit element and to substantially eliminate spurious acoustic reflections caused by the array.

Ultrasonic imaging systems are widely used to produce images of internal structure of a specimen or target of interest. A diagnostic ultrasonic imaging system for medical use forms images of internal tissues of a human body by electrically exciting an acoustic transducer element or an array of acoustic transducer elements to generate short ultrasonic pulses that are caused to travel into the body. Echoes from the tissues are received by the acoustic transducer element or elements and are converted into electrical signals. circuit element, such as a printed circuit board, flexible cable or semiconductor, receives the electrical signals. The electrical signals are amplified and used to form a cross-sectional image of the tissues. These imaging techniques provide a safe, non-invasive method of obtaining diagnostic images of the human body.

The acoustic transducer which radiates the ultrasonic pulses is provided with a plurality of piezoelectric elements arranged in an array with a predetermined pitch. The array is generally one or two-dimensional. By reducing the pitch of the piezoelectric elements in the array, and increasing the number of elements, the resolution of the image can be increased. An operator of the imaging system can control the phase of the electronic pulses applied to the respective piezoelectric elements in order to vary the direction of the output ultrasonic wave beam or its focus. In this way, the operator can "steer" the direction of the ultrasonic wave in order to illuminate desired portions of the human body without needing to physically manipulate the position of the transducer.

When one of the piezoelectric elements is energized, acoustic waves are transmitted both from the front surface facing the imaging target and the rear surface of the element. It is desirable that the acoustic energy from the rear surface be substantially attenuated so that the image resolution is not adversely affected. If not attenuated, the rearward travelling acoustic signals can reflect off the circuit element and return to the transducer surface, causing a degradation of the desired electrical signal.

To remedy this situation, a backing layer of an acoustically attenuating material is disposed between the piezoelectric elements and the circuit element to attenuate the undesired acoustic energy from the rear surface of the piezoelectric element. Ideally, this backing layer would have an acoustic impedance matched to the impedance of the piezoelectric elements so that a substantial portion of the acoustic energy at the rear surface of the piezoelectric element is coupled into the backing layer.

A problem with the use of a backing layer between the piezoelectric element and the circuit element is that of providing electrical interconnection between the particular piezoelectric elements and the associated circuit elements. The interconnection problem is more difficult for two-dimensional arrays of more than three rows and columns of piezoelectric elements, since the internal elements will not have an exposed edge that accommodates electrical connection. In such two-dimensional arrays, electrical interconnection between the individual piezoelectric elements and the electric circuit which receives and processes the electrical signals is generally made in the z-axis direction perpendicular to the array. However, as the number of elements within the array increases, and the pitch between the elements decreases, it becomes increasingly difficult to fabricate this interconnection.

One approach to provide the interconnection through the backing layer is disclosed in U.S. Patent No. 4,825,115 by Kawabe et al., entitled ULTRASONIC TRANSDUCER AND METHOD FOR FABRICATING THEREOF. Kawabe teaches the use of printed wiring boards bonded directly to the piezoelectric array transducer elements. A backing layer is then molded onto the array around the boards, which extend outward from the molded backing layer. While Kawabe provides a reliable interconnection method, the wiring boards provide a surface for reflection of acoustic wave energy within the backing layer, and worsen some of the acoustic attenuating properties of the backing layer.

The deficiencies of the prior art could be overcome if the entire backing layer were formed from a contiguous block of material. In this way, the overall acoustic attenuating ability of the backing layer would be improved. However, the use of a solid backing layer compounds the fabrication problem, in that it is difficult to thread electrical conductors through the solid backing layer.

A secondary problem which increases the difficulty of forming the electrical interconnections is that of undesired cross-talk. Cross-talk is defined as unintended interference between adjacent signal conductors, which occurs via capacitive or inductive coupling. In typical applications, cross-talk can be minimized or eliminated through shielding of the conductive element. While a shield provided around the electrical conductors which form the interconnections through the backing layer would mitigate the cross-talk problem, the shield increases the difficulty of providing the conductors through the solid backing layer.

Therefore, a critical need exists for an improved method and apparatus for making electrical interconnection between elements of an acoustic transducer array and corresponding contacts of an electrical circuit element. Such a technique should provide for the outputted acoustic energy from the rear surface of

the piezoelectric element to be fully attenuated so that there are substantially no reflections of such energy back into the transducer element. The technique should also permit relative ease of manufacture and ready adaptability for large transducer arrays having high numbers of piezoelectric elements with relatively small pitch.

In accordance with the above, this invention provides an acoustic transducer for transmitting acoustic wave energy in response to an electrical signal and for converting the received acoustic wave energy into an electric signal. The acoustic transducer includes an array of piezoelectric elements, a backing layer attached at a rearward face of the piezoelectric elements, a circuit element spaced apart from the piezoelectric elements by the backing layer, and at least one electrical conductor for each of the piezoelectric elements to connect the elements to the circuit element. The backing layer comprises a plurality of layers of acoustic attenuating material integrally formed into a generally laminate structure. The electrical conductors extend along a surface of each of the layers and have a predetermined pitch. Each of the layers has a thickness substantially equivalent to the pitch of the electrical conductors.

In an embodiment of the invention, each of the electrical signal conductors is separated by electrical ground conductors which are not in electrical contact with the electrical signal conductors. The ground conductors would substantially reduce undesired cross-talk between adjacent electrical conductors of a particular layer. Similarly, selected layers could be separated by ground layers to substantially reduce undesired cross-talk between the electrical conductors of adjacent layers.

The invention further provides a method for fabricating the laminate structure from a plurality of layers of acoustic attenuating material. Each of the layers is patterned with a plurality of electrical conductors of a predetermined pitch equivalent to the thickness of the layers. The patterned layers are then combined into the generally laminate structure with the electrical conductors extending between a top and bottom surface of the structure. After combining the individual layers into a laminate structure, electrical contacts would be disposed on the bottom surface of the laminate structure for electrical connection to respective ones of the circuit element electrical contacts. Individual piezoelectric elements of the transducer matrix would be disposed on the top surface of the laminate structure with each of the piezoelectric elements being electrically connected to respective ones of the electrical conductors.

An exemplary embodiment of the invention will now be described with reference to the drawings, in which:

Fig. 1 is an exploded perspective view of a laminate structure of an acoustic transducer backing

layer of this invention;

Fig. 2 is an enlarged view of a portion of an individual layer of Fig. 1;

Fig. 3 is a perspective view of the backing layer of Figs. 1 and 2 combined into a single laminate structure;

Fig. 4 is a partial bottom view of the laminate structure illustrating a pattern of electrical contacts;

Fig. 5 is a partial perspective view of the laminate structure illustrating the individual piezoelectric elements disposed on a top surface of the laminate structure;

Fig. 6 is a partial perspective view of a single layer of the laminate structure as in Fig. 2, illustrating an embodiment in which ground conductors alternate with the electrical conductors;

Fig. 7 is an exploded perspective view as in Fig. 1, in which ground layers are interspersed with the conductive layers;

Fig. 8a illustrates a partial perspective view of a single layer in which a three-sided electrical conductor is utilized;

Fig. 8b is a partial top view of the single layer of Fig. 8a; and

Fig. 9 is an exploded perspective view of an acoustic transducer of this invention.

This invention discloses an improved method and apparatus for making electrical contact between elements of an acoustic transducer array and corresponding contacts of an electrical circuit element. The invention provides for the outputted acoustic energy from the rear surface of the piezoelectric elements to be fully attenuated so that there are substantially no reflections of such energy back into the transducer element. In addition, the invention is relatively easy to manufacture and readily adaptable for large transducer arrays having high numbers of piezoelectric elements with relatively low pitch.

Referring first to Figs. 1-5, a method for making an acoustic transducer from a laminate structure 30 of acoustic attenuating material is illustrated. The laminate structure 30 comprises a plurality of layers 10 (illustrated as layers 10₁ through 10₆) which are formed from initial sheets of acoustic attenuating material that are cut into an approximate shape. In the preferred embodiment, the material is an epoxy having acoustic absorbers and scatterers, such as tungsten, silica, chloroprene particles or air bubbles. While the material is not limited to epoxy, it must be both electrically insulating and acoustically absorbing.

Each of the layers 10 has a front surface 12, a rear surface 14, a top surface 16 and a bottom surface 18. The front surface 12 is provided with an electrode coating 22. The exact thickness of the coating 22 can be selected to exhibit desired acoustic and structural qualities. If the coating 22 is too thick, it

could adversely affect the acoustic properties of the material by increasing reflectivity of the rearward traveling acoustic wave. On the other hand, if the coating 22 is too thin, it could be of low conductivity or prone to discontinuities of conduction. In the preferred embodiment, the electrode coating 22 comprises a two metal coating having a first coating of chromium applied to a thickness of approximately 300 Ångströms, and a second coating of gold applied to a thickness of approximately 3000 Ångströms. The chromium promotes adhesion to the layer 10 and the gold provides a good quality electrical conductor which is resistant to oxidation. However, it should be apparent that alternative materials could be used for the coating 22 as long as the desired electrical conductivity and material strength requirements are satisfied. The metal coatings can be applied by sputtering, plating, or other conventional techniques.

After the conductive coating 22 is applied to each layer 10, the coated layer is patterned to provide a plurality of conductors 24, as shown in Figs. 1 and 2. Each conductor 24 extends between the top edge 16 and the bottom edge 18 of the layer 10, and is separated from adjacent conductors 24 by a gap 26. The patterning could be produced by a diamond saw, with the saw kerf forming the inter-conductor gap 26. The saw should cut into the layer 10 to a slight depth to further promote isolation of the individual conductors 24. Alternatively, the pattern could be produced by conventional photolithographic techniques.

The individual conductors 24 are separated by a desired pitch, which is equivalent to the desired pitch of the piezoelectric elements of the transducer, as will be described below. In the preferred embodiment, the conductors 24 would have a pitch of 300 microns with a gap 26 spacing between each conductor of 50 microns. The particular spacing and pitch shown in the figures is for illustrative purposes only, and is not drawn to scale.

Once a plurality of patterned layers 10 is produced, the layers are combined together into the laminate structure 30 illustrated in Fig. 3. The layers 10 are combined under temperature and pressure with an electrically insulating epoxy or other adhesive which fills the gaps between the individual conductors. Each of the patterned layers 10 is oriented so that the conductors 24 extend between an upper surface 32 and a lower surface 34 of the laminate structure 30. Once the laminate structure 30 is formed, the external surfaces are lapped with conventional machining processes to produce substantially flat and/or orthogonal surfaces. An edge portion 28 of each conductor 24 is exposed at the upper and lower lapped surfaces.

Next, referring to Fig. 4, a pattern of electrical contacts is provided on the lower surface 34 of the laminate structure 30. An electrode coating 38 is applied to the lower surface 34, in the same manner as

the application of the coating 22 to the individual layers 10 described above. The bottom conductor 38 is then patterned to provide a plurality of individual conductive pads 46. Each pad 46 is electrically connected to an associated end of one of the conductors 24, as illustrated in phantom, and is patterned to match associated elements of the circuit element.

The patterning can be produced by a conventional diamond saw, as substantially described above. The saw would first cut a plurality of vertical kerf lines 42 having identical pitch as the gaps 26 between adjacent conductors 24 of the individual layers 10. The saw would then cut a plurality of horizontal kerf lines 44 spaced at midpoints of the individual layer 10 thicknesses. However, other patterning techniques such as photolithography can also be advantageously applied.

Referring now to Fig. 5, on the top surface 32 of the laminate structure 30, a conductive coating 36 is applied in the same manner as that described above. However, prior to patterning the coating 36, a layer of piezoelectric material 48 is bonded onto the conductive coating. The piezoelectric material 48 may include any material which generates acoustic waves in response to an electric field applied across the material, such as but not limited to lead zirconium titanate.

To bond the piezoelectric material 48 to the conductive coating 36, a low viscosity electrically insulating adhesive, such as epoxy, is utilized. The adhesive is applied to a thickness of approximately one micron. The RMS roughness of the piezoelectric material 48 exceeds the bond thickness, so that when heat and pressure are applied the peaks of the piezoelectric material penetrate through the epoxy to form electrical connections between the piezoelectric material and the conductive coating 36.

Once the piezoelectric material 48 has been bonded onto the conductive coating 36, a matching layer 68 of graphite or polymer is applied onto the exposed surface of the piezoelectric material 48. The matching layer 68 increases the forward wave energy produced by the piezoelectric material 48, as known in the art. The combination of the piezoelectric material 48, the conductive coating 36 and the matching layer 68 is then patterned with vertical and horizontal kerf lines 42 and 44 in the same manner as that described above with respect to the bottom surface 34. It should be apparent that this technique permits self-alignment of the top conductive coating 36 to the vertical and horizontal kerf lines 42 and 44 with the laminate structure 30.

It should be apparent that the patterning technique results in a plurality of piezoelectric elements 52 disposed in a matrix each having an electrical conductor 24 extending through the acoustic attenuating backing material of the laminate structure 30 to an electrically conducting pad 46 disposed on a bottom surface 34 of the laminate structure. The pads 46 at

the bottom surface 34 are substantially aligned to the piezoelectric elements 52 on the upper surface 32. A matrix of piezoelectric elements 52 of any desired dimension can be produced in this manner by simply increasing the size and number of the layers 10.

Referring now to Fig. 6, an alternative embodiment of the laminate structure 30 is illustrated. The patterning of each individual layer 10 has alternating electrical signal conductors 62 and ground conductors 64. The pitch of a combined pair of an electrical conductor 62 and a ground conductor 64 is equivalent to the pitch of a single electrical conductor 24 described above. The inclusion of interspersed ground conductors 64 is intended to reduce cross-talk of electrical signals between adjacent ones of the electrical signal conductors 62. The patterning of each layer 10 is performed using a diamond saw or a photolithographic process, as is substantially discussed above. However, at an upper edge of the layer 20, a ground path gap 66 is provided to prevent electrical connection between the ground conductor 64 and the piezoelectric element 52 which would be formed by the method discussed above. At a bottom surface of an assembled laminate structure 30 having the ground conductor 64, the patterning would match the spacing of the individual layer 10 so that distinct conductive pads 46 are produced for the electrical connection between the circuit element and the ground conductors 64 and the electrical conductors 62. It is intended that the ground conductors 64 be electrically connected to a ground potential, so that any cross-talk signal induced into the ground conductors would be shunted to ground.

To control cross-talk between electrical conductors 24 of adjacent layers 10, a second alternative embodiment is illustrated in Fig. 7. In this embodiment, individual layers 10 would be divided in width through a first layer portion 72 and a second layer portion 74. A ground plane 76 is disposed between the first and second layer portions 72 and 74. The ground plane would similarly connect electrically to ground pads 46 disposed at the lower surface 34 of the assembled laminate structure 30, so as to shunt undesired cross-talk signals to ground. In a similar manner, thermal conductors could be used in place of the ground planes 76 to eliminate excess heat from within the laminate structure 30. The thermal conductors would conduct excess heat within the structure 30 to an external heat sink (not shown).

Experimentation with acoustic transducers formed in accordance with the teachings of this invention has demonstrated acceptable levels of cross-talk attenuation for steering and focusing of a two-dimensional array. In particular, intra-layer cross-talk levels measured between adjacent conductors 24 demonstrate a cross-talk signal of -46 Db. Similarly, inter-layer cross-talk measurements made between conductors 24 of adjacent layers 10 demonstrate a cross-

talk signal of -45 dB. It is anticipated that further improvements in cross-talk attenuation can be obtained through use of the interspersed ground conductors 64 described above.

It is estimated that the individual electrical conductors 24 would dissipate low levels of electrical power, and thus would present a minimal thermal problem. The measured resistance for each individual conductor 24 is less than 1 ohm. Since the individual piezoelectric elements 52 have resistance of approximately 10,000 ohms and require approximately 100 volts for the transmit pulse, each conductor 24 can be expected to carry approximately 10 milliamps. Thus, each electrical conductor 24 could be expected to dissipate approximately 100 microwatts, which is relatively low.

However, it may be desirable in certain applications to further reduce the resistance and increase the reliability of each conductor 24. Accordingly, Figs. 8a and 8b illustrate a third alternative embodiment of the invention. Rather than providing a single planar electrical conductor 24 which is patterned as described above, the individual layers 10 are patterned prior to applying the conductive coating 22 to form generally rectangular grooves 82. The rectangular grooves 82 are then coated with an electrically conductive coating including an electrically conductive backwall 84 and conductive sidewalls 86. The three-sided electrical conductor 80 is then filled with an electrically insulating epoxy 88, and the individual layers are combined as substantially described above into the single laminate structure 30. As before, bottom conductive pads 46 are formed on the lower surface of the laminate structure 30, and individual piezoelectric elements 52 are disposed on an upper surface of the laminate structure. The three-sided conductor 80 would have a resistance roughly one-third of the conductor 24 described above.

Fig. 9 illustrates an exploded perspective view of an acoustic transducer 50 constructed in accordance with this invention. The transducer 50 attaches electrically to a circuit element illustrated as printed circuit board 54. The circuit element can also be a semiconductor, flexible cable or other device. The circuit board 54 has a plurality of electrical contact points 56 which match the position of the individual conductive pads 46 at the lower surface 34 of the transducer 50. In addition, a ground sheet 58 overlays the exposed upper portion of the individual piezoelectric elements 52 and electrically connects to the individual elements.

In operation, the circuit board 54 provides electrical signals to the individual conductive pads 46 of the transducer 50. The electrical signals are conducted via the electrical conductors 24 through the layers 10 of the laminate structure 30 to the rearward surface of the individual piezoelectric elements 52. The acoustically transparent ground sheet 58 is disposed

on the exposed surface of the transducer 50, and is placed in contact with the object of interest, such as the patient's skin. Utilization of the ground sheet 58 at the exposed surface of the piezoelectric elements 52 rather than at the rearward surface prevents the patient from receiving an inadvertent electrical shock.

The electrical signals which are inputted to the piezoelectric elements 52 are converted into acoustic wave energy which is transmitted through the ground sheet 58 into the subject. The wave energy transmitted from the transducer 50 is utilized to achieve echographic examination. The undesirable transmission of acoustic wave energy from the rearward faces of the piezoelectric elements 52 is absorbed by the laminate structure 30 formed from the acoustic absorbing material. Reflected wave energy received at the piezoelectric elements 52 is converted to an electrical signal that is conducted back through the electrical conductors 24 to the circuit board 54. This received signal would then be conditioned by known electrical circuitry on the circuit board.

Using the invention, an array of any desired dimension can be produced by varying the number and size of the layers 10, and the pitch of the conductors 24 disposed on each layer.

Claims

1. A backing layer for interfacing an acoustic transducer array having a plurality of transducer elements (52), each of which has a first acoustic impedance and a rear face, with an electric circuit element (54) having a contact (56) for each transducer element, the backing layer comprising:

a plurality of layers (10) of acoustic attenuating material integrally formed into a block (30) having a first face (32) and a second face (34), the block (30) having an acoustic impedance at the first face (32) which is of a value relative to the first acoustic impedance such that a selected portion of the element acoustic energy at the rear face is coupled into the block (30);

at least one electrical conductor (24) for each of the transducer elements (52), the conductors (24) extending between the first (32) and second (34) faces and having a predetermined pitch, the conductors (24) for adjacent transducer elements (52) being electrically isolated from one another;

a plurality of first electrical contacts (36) disposed at the first face (32) for effecting electrical connection between the rear face of each transducer element and the corresponding at least one electrical conductor (24); and

a plurality of second electrical contacts (46) disposed at the second face (34) for effecting electrical connection between the circuit ele-

ment contact (56) for the transducer element (52) and the corresponding at least one electrical conductor (24).

2. The backing layer of Claim 1 wherein the electrical conductors (24) are disposed on a surface of each of the layers (10).
3. The backing layer of Claim 1 or 2 wherein the first electrical contacts (36) are disposed in a pattern substantially matching the rear face of the transducer array.
4. The backing layer of Claim 1, 2 or 3 wherein the second electrical contacts (46) are disposed in a pattern substantially matching the electric circuit contacts (56).
5. The backing layer of any one of the preceding claims wherein the electrical conductors (62) are separated by ground conductors (64), the electrical conductors (62) being electrically isolated from the ground conductors (64).
6. The backing layer of any one of the preceding claims wherein selected ones of the layers (10) further include electrical shielding (76) to electrically isolate electrical conductors (24) of adjacent ones of the layers (10).
7. A method for fabricating an acoustic transducer having a plurality of piezoelectric elements (52) aligned in a matrix, the method comprising the steps of:
 - providing a laminate structure (30) comprising a plurality of layers (10) of an acoustic attenuating material, each of the layers (10) having a plurality of electrical conductors (24);
 - disposing electrical contacts (46) on a bottom surface (34) of the laminate structure (30) electrically connected to respective ones of the electrical conductors (24), the electrical contacts (46) capable of connection to an external power source; and
 - disposing the piezoelectric elements (52) on a top surface (32) of the laminate structure (30), the piezoelectric elements (52) being electrically connected to respective ones of the electrical conductors (24).
8. The method for fabricating an acoustic transducer of Claim 7 wherein the step of providing a laminate structure further comprises the steps of:
 - providing an electrically conductive coating (22) on a surface of each layer (10);
 - patterning each of the coated surfaces to form the electrical conductors (24); and
 - combining the plurality of layers (10) to-

gether into the laminate structure (30), the electrical conductors (24) extending between the top (32) and bottom (34) surfaces.

9. The method for fabricating an acoustic transducer of Claim 7 or 8 wherein the step of disposing electrical contacts (46) on a bottom surface (34) of the laminate structure (30) further comprises the steps of:
- applying an electrically conductive coating (38) to the bottom surface (34); and
 - patterning the electrically conductive coating (38) to provide the electrical contacts (46).
10. The method for fabricating an acoustic transducer of Claim 7, 8 or 9 wherein the step of disposing the piezoelectric elements (52) on a top surface (32) of the laminate structure (30) further comprises the steps of:
- applying an electrically conductive coating (36) to the top surface (32) and bonding a piezoelectric layer (48) onto the electrically conductive coating (36); and
 - patterning both the electrically conductive coating (36) and the piezoelectric layer (48) to provide the piezoelectric elements (52).

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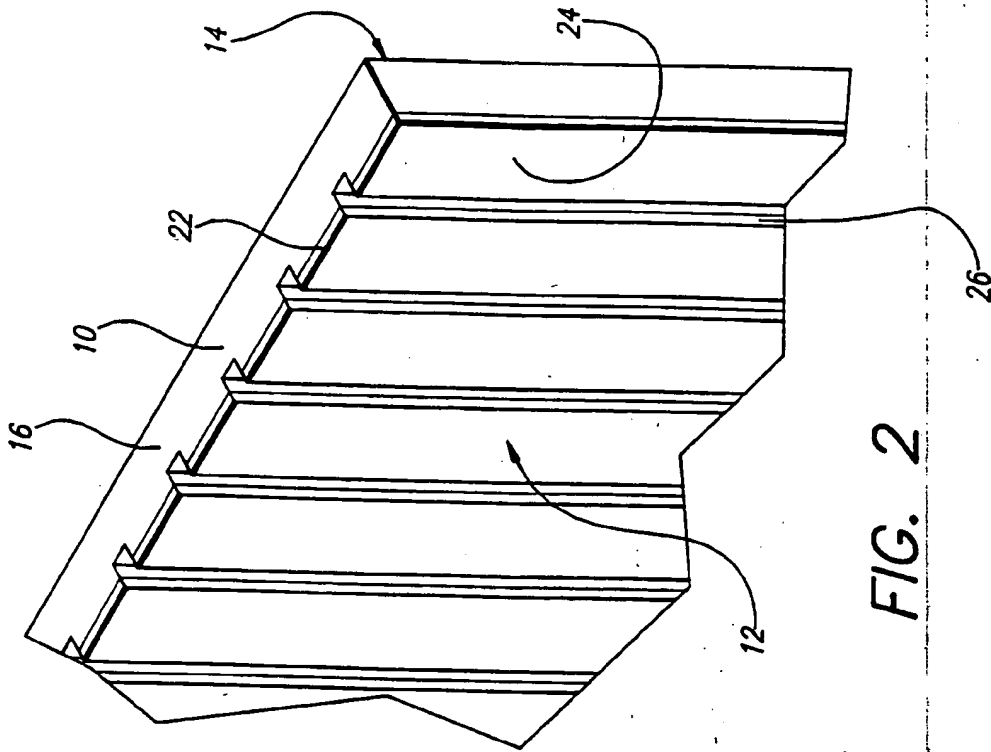


FIG. 2

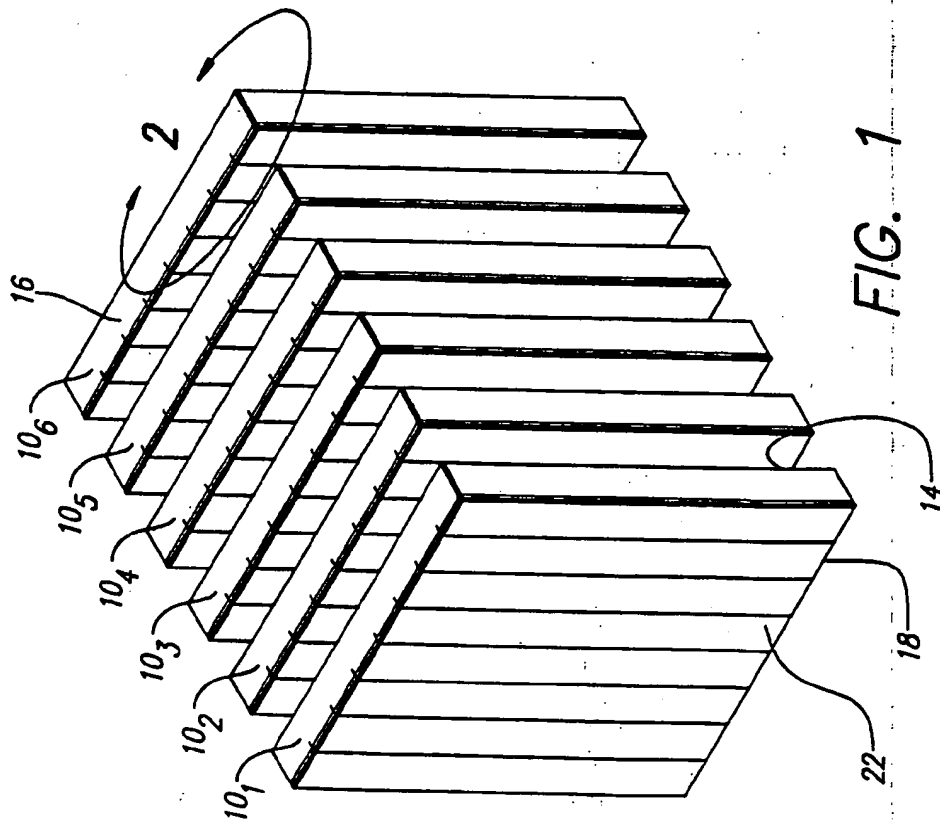
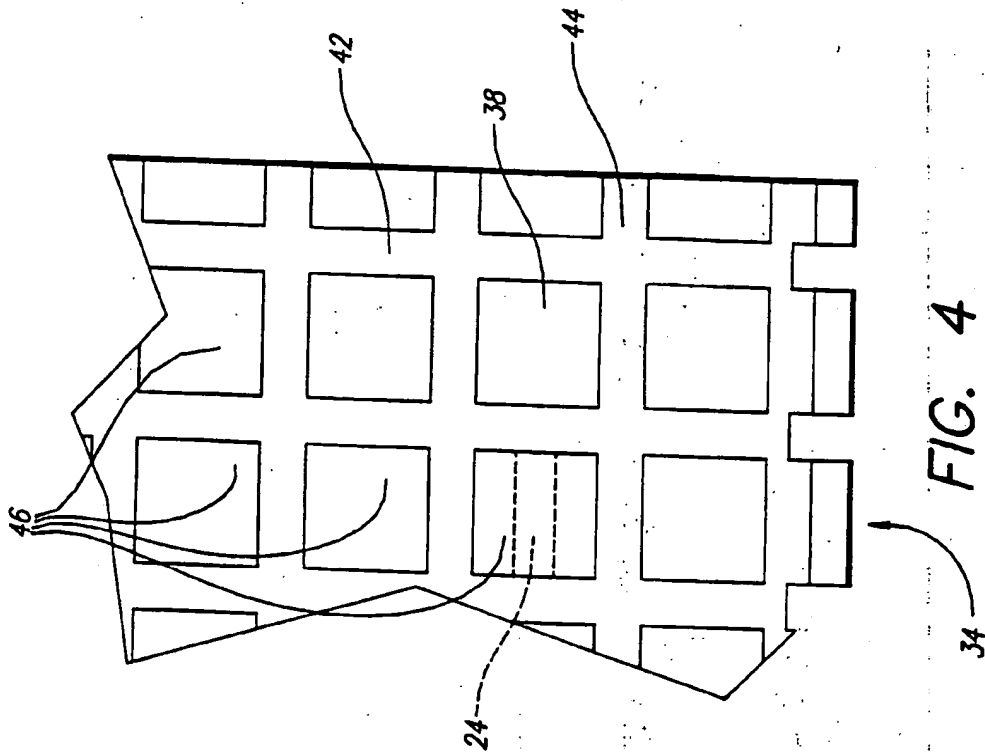
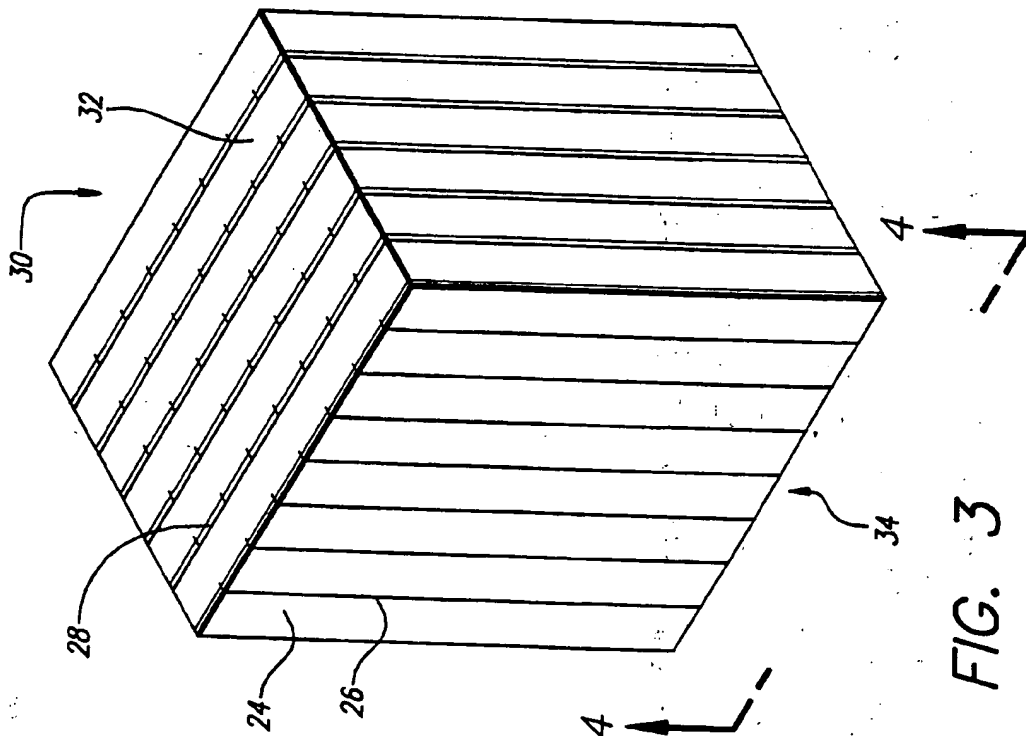


FIG. 1



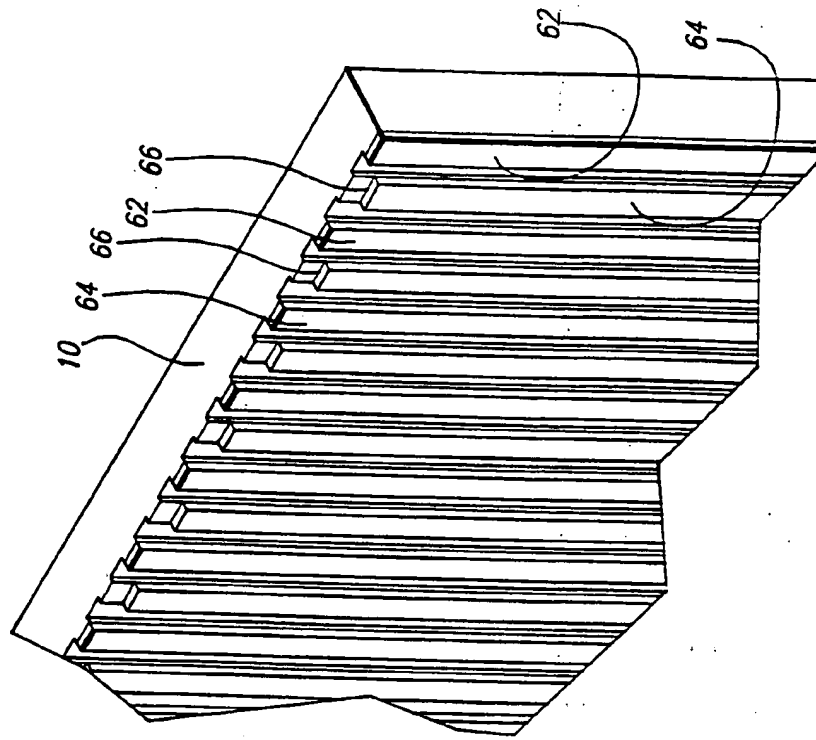


FIG. 6

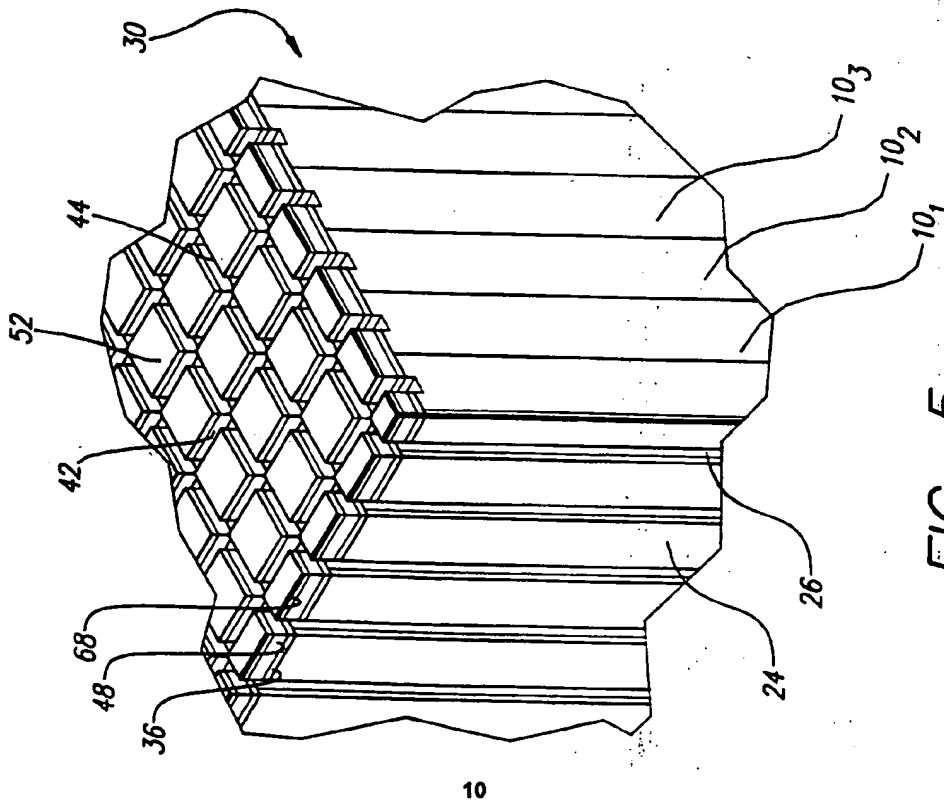


FIG. 5

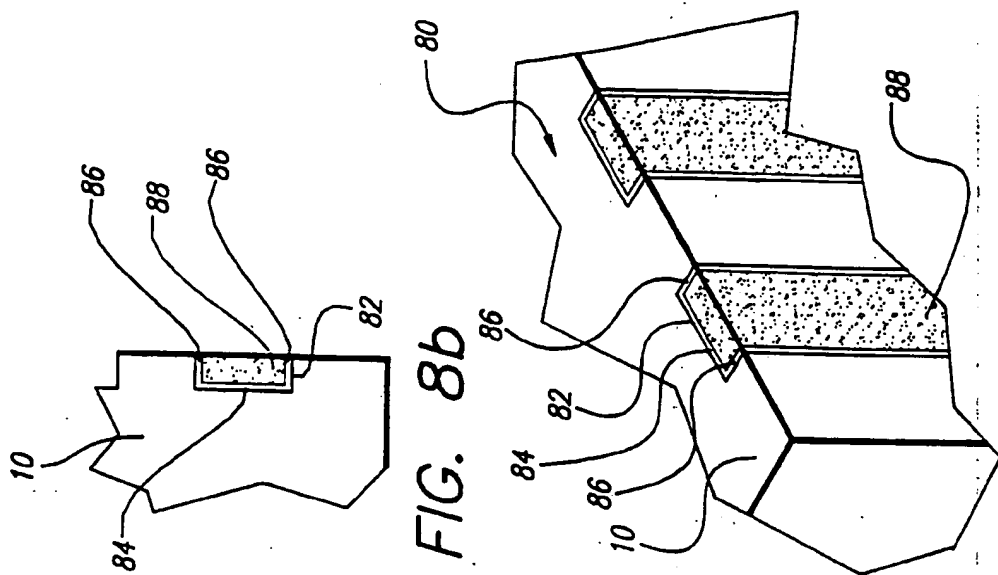


FIG. 8a

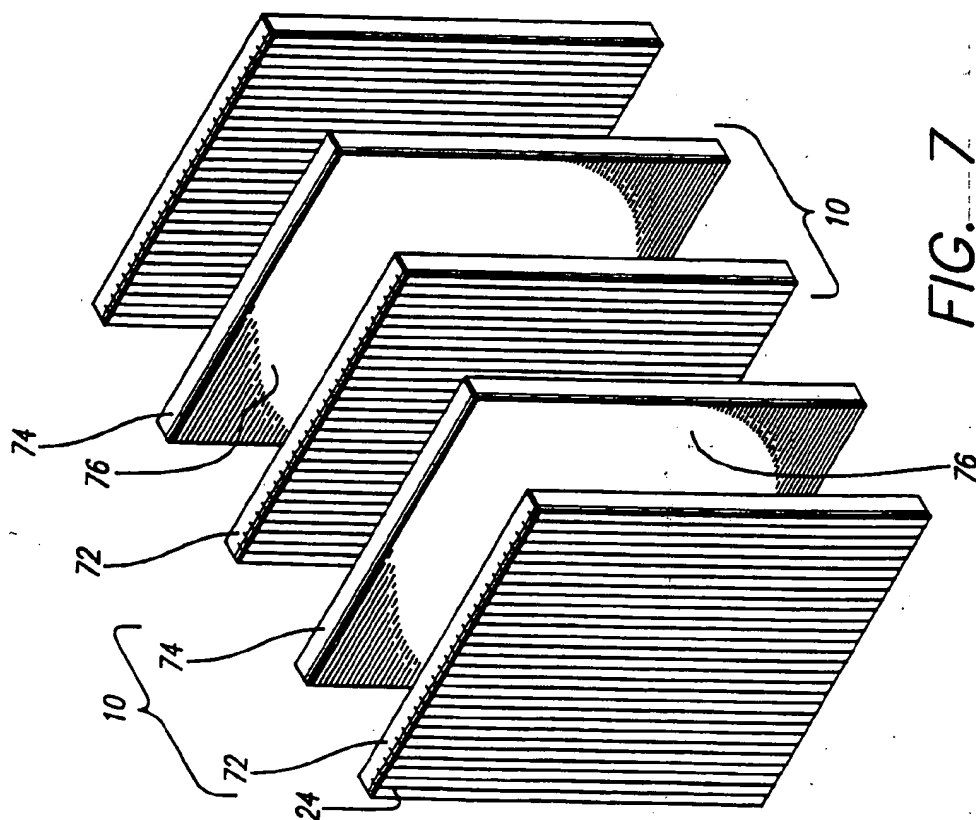


FIG. 7

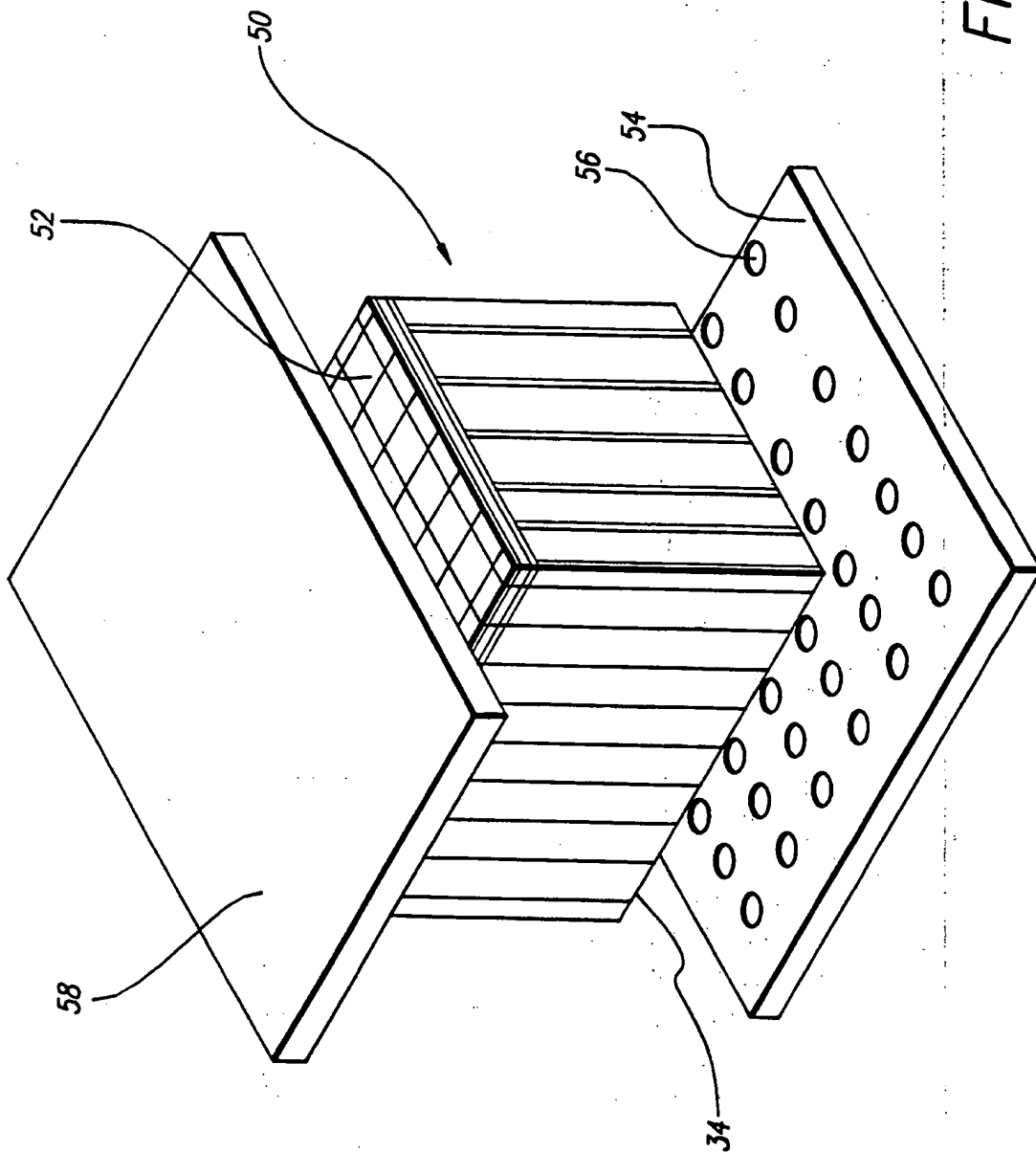


FIG. 9

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